IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In Re the Application of:	)	Group Art Unit: 3672
	)	
Jackson et al.	)	Examiner: SINGH, SUNIL
	)	
Serial No.: 10/688,216	)	Confirmation No.: 7252
	)	
Filed: 10-15-2003	)	REQUEST FOR CONSIDERATION OF
	)	INFORMATION DISCLOSURE
Atty. File No.: 5885-1	)	STATEMENT SUBMITTED DECEMBER
	)	18, 2006
For: AUTOMATED EXCAVATION	)	
MACHINE	)	Electronically Submitted

Mail Stop Issue Fee
Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

Dear Sir:

On December 18, 2006, Applicants submitted an Information Disclosure Statement (IDS) in the above-identified patent application. The Information Disclosure Statement, including the non-patent literature references and the EFS Acknowledgment Receipt, is attached hereto as Exhibit A.

On September 4, 2009, the Examiner issued a Notice of Allowance for the above-identified case. A review of the file has indicated that the Examiner has yet to consider the IDS filed on December 18, 2006.

Applicants hereby respectfully request that the Information Disclosure Statement of December 18, 2006, be considered by the Examiner.

Although no fees are believed due in connection with this communication, please charge any fees deemed necessary to Deposit Account No. 19-1970. If additional information is required please contact the undersigned.

Respectfully submitted,

SHERIDAN ROSS P.C.

By: EKelly

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Registration No. 62288
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(303) 863-9700

Date: 12-4-09

Exhibit A

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In Re the Application of:	)	Group Art Unit: 3673
	)	
JACKSON et al.	)	Confirmation No.: 7252
	)	
Serial No.: 10/688,216	)	Examiner: SINGH, SUNIL
	)	
Filed: October 15, 2003	)	<u>SUPPLEMENTAL INFORMATION</u>
	)	<u>DISCLOSURE STATEMENT</u>
Atty. File No.: 4770-37	)	
	)	Electronically Submitted
For: "AUTOMATED EXCAVATION	)	
MACHINE"	)	

Mail Stop Amendment
Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

Dear Sir:

The references cited on attached Form PTO-SB08 are being called to the attention of the Examiner.

☒ Copies of the cited non-patent and/or foreign references are enclosed herewith.

☐ Copies of the cited U.S. patents and/or patent applications are enclosed herewith.

☒ Copies of the cited U.S. patents/patent application publications are not enclosed in accordance with 37 C.F.R. § 1.98(a).

☐ Copies of the cited references are not enclosed, in accordance with 37 C.F.R. § 1.98(d), because the references were cited by or submitted to the U.S. Patent and Trademark Office in prior application Serial No. __________ filed ______________, which is relied upon for an earlier filing date under 35 U.S.C. § 120.

☐ To the best of applicants' belief, the pertinence of the foreign-language references are believed to be summarized in the attached English abstracts and in the figures, although applicants do not necessarily vouch for the accuracy of the translation.

☐ Examiner's attention is drawn to the following co-pending applications, copies of which have been or are being submitted:

Serial No. ________________ filed ______________

Serial No. ________________ filed ______________

☐ Other:____

Submission of the above information is not intended as an admission that any item is citable under the statutes or rules to support a rejection, that any item disclosed represents analogous art, or that those skilled in the art would refer to or recognize the pertinence of any reference without the benefit of hindsight, nor should an inference be drawn as to the pertinence of the references based on the order in which they are presented. Submission of this statement should not be taken as an indication that a search has been conducted, or that no better art exists.

It is respectfully requested that the cited information be expressly considered during the prosecution of this application and the references made of record therein.

FEES

☐	37 CFR 1.97(b): No fee is believed due in connection with this submission, because the Information disclosure statement submitted herewith is satisfies one of the following conditions ("X" indicates satisfaction): ☐ Within three months of the filing date of a national application other than a continued prosecution application under 37 CFR 1.53(d), or ☐ Within three months of the date of entry into the national stage of an international application as set forth in 37 CFR 1.491 or ☐ Before the mailing date of a first Office Action on the merits, or ☐ Before the mailing of a first Office action after the filing of a request for continued examination under 37 CFR 1.114. Although no fee is believed due, if any fee is deemed due in connection with this submission, please charge such fee to Deposit Account 19-1970.
☒	37 CFR 1.97(c): The information disclosure statement transmitted herewith is being filed after all the above conditions (37 CFR 1.97(b)), but before the mailing date of one of the following conditions: (1) a final action under 37 C.F.R. 1.113 or (2) a notice of allowance under 37 C.F.R. 1.311, or (3) an action that otherwise closes prosecution in the application. This Information Disclosure Statement is accompanied by: ☐ A Certification (below) as specified by 37 C.F.R. 1.97(e). Although no fee is believed due, if any fee is deemed due in connection with this submission, please charge such fee to Deposit Account 19-1970. OR ☒ Please charge Deposit Account 19-1970 in the amount of $180.00 for the fee set forth in 37 C.F.R. 1.17(p) for submission of an information disclosure statement. Please credit any overpayment or charge any underpayment to Deposit Account 19-1970.
☐	37 CFR 1.97(d): This Information Disclosure Statement is being submitted after the period specified in 37 CFR 1.97(c). ☐ This Information Disclosure Statement includes a Certification (below) as specified by 37 C.F.R. 1.97(e) AND ☐ Applicants hereby requests consideration of the reference(s) disclosed herein. Please charge Deposit Account 19-1970 in the amount of $180.00 under 37 C.F.R. 1.17(p). Please credit any overpayment or charge any underpayment to Deposit Account 19-1970. Election to pay the fee should not be taken as an indication that applicant(s) cannot execute a certification.

Certification (37 C.F.R. 1.97(e))
(Applicable only if checked)

☐ The undersigned certifies that:

☐ Each item of information contained in this information disclosure statement was first cited in any communication from a foreign patent office in a counterpart foreign application not more than three months prior to the filing of this statement. 37 C.F.R. 1.97(e)(1).

☐ A copy of the communication from the foreign patent office is enclosed.

OR

☐ No item of information contained in this information disclosure statement was cited in a communication from a foreign patent office in a counterpart foreign application, and, to the knowledge of the undersigned after making reasonable inquiry, no item of information contained in this Information Disclosure Statement was known to any individual designated in 37 C.F.R. 1.56(c) more than three months prior to the filing of this statement. 37 C.F.R. 1.97(e)(2).

Respectfully submitted,

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Date: Dec. 18, 2006

Substitute for form 1449A/PTO				Complete if Known	
INFORMATION DISCLOSURE STATEMENT BY APPLICANT				Application Number	10688216
				Filing Date	10/15/03
				First Named Inventor	Jackson
				Art Unit	3673
				Examiner Name	SINGH, SUNIL
Sheet	1	of	1	Attorney Docket Number	4770-37

U.S. PATENT DOCUMENTS					
Examiner Initials*	Cite No.[1]	Document Number Number-kind Code [2] (if known)	Publication Date MM-DD-YYYY	Name of Patentee of Applicant of Cited Document	Pages, Columns, Lines, Where Relevant Passages or Relevant Figures Appear
	1	919,105	4/20/1909	Wischow	
	2	1,365,748	1/18/1921	Thorn	
	3	3,620,573	4/10/1969	Desmond De Villiers Oxford	
	4	4,123,109	10/31/1978	Hill	
	5	4,213,653	7/22/1990	Grenia	
	6	4,293,077	10/6/1981	Makino	
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	8	4,523,651	6/18/1985	Coon et al.	
	9	5,662,387	9/2/1997	Bartkowiak	
	10	6,304,973	10/16/2001	Williams	
	11	6,431,654	8/13/2002	Kleuters	
	12	2004/0207247	10/21/2004	Jackson et al.	

FOREIGN PATENT DOCUMENTS						
Examiner Initials*	Cite No.[1]	Foreign Patent Document Country Code[3]; Number[4]; Kind Code[5] (if known)	Publication Date MM-DD-YYYY	Name of Patentee or Applicant of Cited Document	Pages, Columns, Lines, Where Relevant Passages or Relevant Figures Appear	T[6]

OTHER ART (Including Author, Title, Date, Pertinent Pages, etc.)		
Examiner Initials*	Cite No.[1]	
	13	Asbury et al., "A New Concept for Selective Mechnanical Mining of Hard Rock", date unknown
	14	Friant et al., "Mini-Cutter Technolgy - The Answer To A Truly Mobile Excavator", Proceedings of North American Tunneling 1994 Conference and Exhibition; Denver, Colorado, June 6-9, 1994; 8 pages
	15	Ronnkvist et al., "Development Of A Mechanical Alcove Excavator For the Yucca Mountain Exploratory Study Facility", 6 pages, date unknown
	16	Ronnkvist et al., "Testing And Performance Evaluation Of A 32 Inch Cutterhead Using Mini Disc Cutters", Proceedings of ISDT Annual Technical Conference 1994; Las Vegas, Nevada; April 18-21, 1994; 8 pages
	17	Rostami et al., "Mini-Disc Equipped Roadheader Technology for Hard Rock Mining", p. 16-1 to 16-12, Golden, Colorado, date unknown

Examiner Signature		Date Considered	

*EXAMINER: Initial if reference is considered, whether or not citation is in conformance and not considered. Include copy of this form with next communication to applicant.

A New Concept for Selective Mechanical Mining of Hard Rock

Brian Asbury[1], Jamal Rostami[1], and Levent Ozdemir[1]

[1] EARTH MECHANICS INSTITUTE, MINING ENGINEERING DEPARTMENT, COLORADO SCHOOL OF MINES

ABSTRACT

Over the last several decades mechanical mining machines have developed into highly productive, light weight, mobile machines which are able to economically mine many soft rock ore bodies. Due to the utilization of disc cutters Tunnel Boring Machines, with great mass and limited mobility, have developed the ability to cut the hardest rocks at high production rates. Technological advancements have allowed mini-disc cutters, which require low forces to cut hard rock, to be developed. These mini-disc cutters provide a new option for developing a light weight, mobile machine which can excavate hard rock. This concept and supporting data are presented.

BACKGROUND

Current economically viable mechanical mining machines utilize drag type cutters. Drag type cutters are used because they require relatively low forces to cut rock, therefore may be utilized on lightweight mobile machines. These machines are desirable for mining because their mobility allows them to immediately turn in a heading and produce openings with flat floors. The same drag cutters, which allow mechanical mining machines to be mobile, also, provide the limiting factor for being able to cut hard rock.

The most robust of drag cutters are able to cut intact rock of approximately 10,000 to 12,000 psi compressive strength. If the rock is highly fractured, drag cutters can excavate rock of 14,000-16,000 psi by plucking chunks of the rock out from the joint structure. This limitation is caused by friction and impact force of draging the carbide tipped tool through the rock. The harder and more abrasive rock generates more friction and higher impact forces, thus reducing the life of the drag cutters and their economic viability. Figure 1. Illustrates two types of drag cutters.

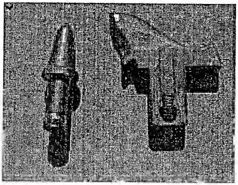

Figure 1: A conical (left) and a radial cutter.

While mechanical mining machines have evolved to suit the soft rock mining community, Tunnel Boring Machines (TBM's) have developed into excavators which can advance through hard rock at very fast rates. The ability to excavate hard rock is due to the use of rolling cutters. Large, single disc cutters have developed into the most efficient and economic rolling cutters for hard rock TBM's. The typical disc cutters, 17 inches in diameter, require a large amount of force to be pressed into hard rock. In order to provide the high forces, required for the large disc cutters, TBM's are massive machines which occupy the entire width of the tunnel. In turn the size of the TBM's greatly inhibit their mobility, resulting in turning radii on the order of 100 of feet or more.

Over the last several years, small diameter cantilever mounted disc cutters have developed into useful hard rock cutting tools. This development has been greatly due to advancement in metallurgy and associated bearing technologies. These small (mini-disc) cutters have been used in extensive laboratory tests, cutting rock with compressive strengths of 5,000 to 42,000 psi. Laboratory testing has included 3.25, 5, and 6 inch mini-disc cutters individually and on cutter heads of 8 inches to 3 feet in diameter. The main result of the testing is that, a 5 inch diameter disc cutter requires an average of $1/7^{th}$ the force to penetrate a given distance into a given hard rock, when compared to the standard 17 inch disc cutter. The difference in force is directly related to the volume of rock being displaced by the cutters. This phenomenon allows for a small, lightweight machine, in the form of a partial face drum excavator, to effectively cut hard rock. Figure 2 presents a typical 17 inch disc cutter ring and a 5" mini-disc.

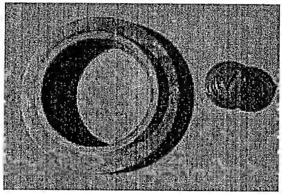

Figure 2: 17 inch disc cutter (left) and 5" mini-disc

INTRODUCTION OF THE DRUM CONCEPT

The drum excavator is a partial face machine with a cutterhead in the shape of a drum, therefore the name drum excavator. The front of the drum is similar to a miniature TBM and is designed to bore to a specific depth. The side of the drum is also dressed with cutters, which cut the rock in a slewing mode. By slewing the drum parallel to the

face and cutting the rock with the cutters that are mounted on the side of the drum, a flat floor is created, which is a great advantage in many underground operations. Also, the face is flat, allowing the machine to work very close to the face which is desirable for machine stability and installing ground control measures.

The first application of this cutting concept was studied for an alcove excavator for the Department of Energy's Yucca Mountain Experimental Study Facility (ESF). For this project, there is a need to excavate alcoves on the side of a TBM bored tunnel while the TBM is operating further down the tunnel. This required a very compact mobile excavator (Figure 3) which could excavate the alcoves with minimum interference to utilities and production in the main tunnel. In support of this project, a 3 foot diameter cutterhead, dressed with 5 inch mini-disc cutters, was designed, built, and tested.

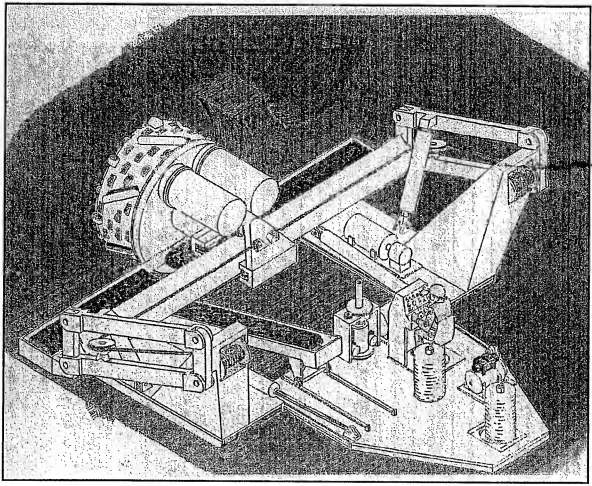

Figure 3: Initial artist rendering of the mobile drum excavator

DESIGN OF THE DRUM CUTTERHEAD

The design of the drum cutter head was based on individual cutter data from the rock to be cut and empirical/theoretical balancing and performance models developed at the Earth Mechanics Institute. Before the drum design could be performed, the force penetration response of the mini-disc working in the target rock had to be well understood. The individual cutter data was generated through a series of linear cutting tests (Figure 4), performed at different spacings and penetrations. The results of this initial test program were used to feed the algorithms of the design models.

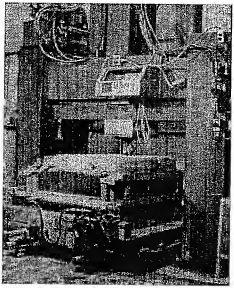

Figure 4: 5" MD on LCM

Disc cutters last longer and are more efficient when side load to the cutters are minimized. In order to prevent the face and side cutters from scuffing, when they are not advancing the face, the gage cutter are protruded outward to cut relief. This can be seen in the cutterhead profile, shown in Figure 5. Therefore, when the cutterhead is sumping, the side cutters are not touching the rock, and when the cutterhead is slewing, the face cutters are not in contact.

Disc cutters are known to work best under stable cutting conditions. The design model was therefore used to balance the cutterhead to minimize fluctuations in forces during the cutting action. This is particularly important because the drum cutterhead in slewing mode is a partial face machine since the cutters enter and exit the rock. This results in constantly varying cutter penetration during slewing.

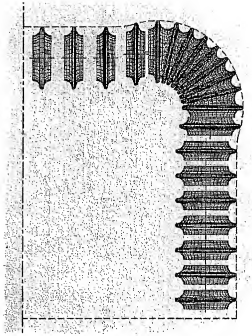

Figure 5: Drum cutterhead profile.

In general, more cutters (close spacing) provide a smoother running and better balanced cutterhead. However, wider spacing requires lower overall force and is more efficient. The goal is to reach the optimum spacing/penetration ratio and to find the largest functional spacing in this region. This results in the most efficient excavation of the rock. Iterations of the design model provide the preferred medium between acceptable force variations and the most efficient cutting, resulting in the highest productivity. Figure 6 is shows the final drum design.

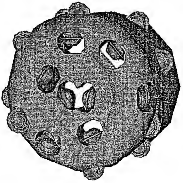

Figure 6: Final 3' cutterhead design

TESTING OF THE DRUM CUTTERHEAD

The drum cutterhead was tested, in both modes of operation, while cutting concrete and welded tuff. The goal of the test program was to validate the drum cutting concept and the computer performance model developed for cutterhead design and balancing. The test data presented here is with the cutterhead turning at approximately 25 rpm.

The laboratory testing of the drum cutting concept was performed on the Drill Test Fixture (DTF) at EMI. The DTF (Figure 7) is able to provide 150 hp of cutting power, 40 tons of thrust/sumping force, and 15 tons of slewing/side cutting force. All operations (i.e. torque, rpm, rpm, and thrust) are measured and recorded by a computer based data acquisition system at a rate of 75 Hz.

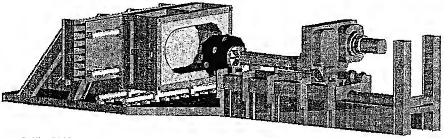

Figure 7: The DTF .

Tests in concrete

The first set of testing for the drum cutterhead was performed while cutting concrete. The concrete was a 6 sack construction grade of approximately 6, 000 psi compressive strength, with 1 inch aggregate of 42,000 psi granitic gniess. Sumping test were performed in concrete at several different thrust forces, to provide data to build thrust vs. advance rate vs. power consumption curves. Sumping in concrete reached a maximum penetration rate of 28 ft/hr. This was accomplished with a thrust of only 52,400 lb and a torque of 19,500 ft-lb. This is equivalent to a production rate of 7.3 yd^3/hr with a power consumption of 90 hp.

Due to the structure of the DTF, slewing loads were limited to 30,000 lb. A slewing rate of 33.5 ft/hr was achieved with a slewing force of 28,000 lb and torque of 21,700 ft-lb. The slewing force, torque and their relationship increased linearly with the slewing rate. The power consumption for this slewing rate was 102 hp, corresponding to a production rate of 7.4 yd^3/hr.

Tests in welded tuff

The test sample was prepared using two large blocks of the TSw2 formation obtained from the Yucca Mountain site. The blocks were cast with concrete in a rock box to provide a confined sample. The measured compressive strength of the welded tuff used in the sumping portion of the sample was 42,000 psi. The rock sample used for the slewing test had a measured compressive strength of 28,000 psi. The samples of welded tuff selected were the hardest available from the samples provided to EMI.

During sumping, a thrust of 71,000 lb resulted in the maximum penetration rate of 15.5 ft/hr at a cutterhead speed of 23 rpm, consuming 85 hp. The penetration rate increased at a higher rate as thrust increased. This means the cutting becomes more efficient as the penetration increases and larger chips are produced.

For the slewing tests, a maximum penetration rate of 25 ft/hr was achieved with a slewing force of 29,300 lb and torque of 25,500 ft-lb. This test, with a production rate of 5.5 yd^3/hr, used 108 hp. A picture of the slewing tests with the drum cutterhead in welded tuff is shown in Figure 8. A summary of the maximum test results for cutting concrete and welded tuff is presented in Table 1.

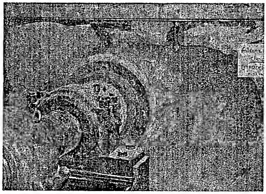

Figure 8: Slewing test in Welded Tuff

Material	Cutting Mode	Thrust (lbf)	Torque (ft-lb)	Power (hp)	Advance (ft/hr)	Production (yd^3/hr)
Concrete	Sump	52,400	19,500	90	28	7.3
Concrete	Slew	28,000	21,700	102	34	7.4
W.Tuff	Sump	71,100	19,200	85	16	4.0
W. Tuff	Slew	29,300	25,500	108	25	5.5

Table 1: Test results of the 36" durm cutterhead.

The laboratory testing of the drum cutterhead in concrete and the welded tuff was very successful. High rates of penetration were achieved with low forces for both sumping and slewing actions. In both cases, the cutting action was observed to be highly efficient with full interaction between adjacent cutter paths. The cutterhead was found to run very smoothly, indicating a well-balanced cutter layout and validating the computer design model used for cutterhead balancing. No cutter failure or noticeable wear was experienced during the entire test program.

The forces imposed on the cutterhead during testing were limited by the available torque and slewing thrust capacities of the test rig. The maximum allowable slew force on the laboratory test rig is 15 tons. The cutterhead is capable of sustaining much higher loads without exceeding the recommended load capacity of individual cutters. This means that much higher penetration and production rates can be attained with a field machine fitted with more power and thrust than the test fixture used in the laboratory. This is especially true for the slewing tests.

MACHINE PRODUCTION ESTIMATES

Initial performance predictions have been made for two different configurations of the mobile mechanical drum miner operating in the 25-30 ksi igneous rock. The configuration is for a 4 foot diameter cutter head. This head would make a 2 foot deep sump before slewing and be provided with 180 hp available for cutting power.

A scenario of mining an 8 foot high by 15 foot wide heading is presented. The 4 foot cutterhead would have to make 2 slewing passes across the face before the machine could advance. A reaction mass of only 41 tons would allow the cutterhead to perform the sumping and slewing actions.

The 4 foot diameter cutterhead is expected to produce 12.9 and 13.7 yd^3/hr instantaneously while sumping and slewing, respectively. Allowing 10 minutes for repositioning each cycle, the miner should advance the heading at a rate of 2.7 ft/hr. These results are presented in Table 2.

Operation	Production
Sumping Rate (yd3/hr)	12.9
Slewing Rate (yd3/hr)	13.7
Heading Advance Rate (ft/hr)	2.7

Table 2: Production rates in 25-30 ksi rock

Assuming a mechanical availability of 90% and a utilization of 80%, the mobile hard rock excavator should be able to advance the heading 16 feet per shift. If the excavator was run two shifts per day, reserving the third shift for maintenance, 32 feet of advance per day could be realized. This is competitive with drill and blast methods.

CONCLUSIONS

There now exists a technically viable, and potentially economic, method for mechanically mining hard rock. This is possible due to the development of the mini-disc cutters and their ability to cut hard rock with relatively low forces. When the mini-disc cutters are utilized with the drum cutting method, hard rock may be mechanically excavated, at reasonable production rates, with a lightweight mobile excavator.

This mechanical option can be competitive and much safer than drill and blast methods. Economic trade off studies, examining mechanical methods, should include the savings generated by many factors; including reduced ground support and ventilation requirements, extended rubber tire life and the elimination of primary crushing.

The next step in this development effort is to build a prototype for full-scale field testing in hard rock. This will provide quantification of the technical and economic viability of the mobile hard rock mechanical excavator.

REFERENCES OF MMA 95 PAPER

Friant, J.E., Ozdemir, L. and Ronnkvist, E., 1994, "Mini-cutter Technology - The Answer to a Truly Mobile Excavator", *Proc. of North American Tunneling '94 Conference and Exhibition*, Denver, Colorado, June 6-9.

Friant, J.E., Rönnkvist, E., Ozdemir, L., 1993, "Alcove Excavator for the Yucca Mountain Experimental Study Facility", Report prepared for RSN contract # SC-YM-93-159, EMI, CSM.

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Rostami, J., Neil, D.M., Ozdemir, L., 1993, "Roadheader Application for the Yucca Mountain Experimental Test Facility", Report prepared for RSN contract # SC-YM-93-159, EMI, CSM.

Rönnkvist, E., Ozdemir, L., Friant, J.E., 1994, "Testing and Performance Evaluation of a 32 inch Cutterhead using Mini Disc Cutters", *Proc. of Institute of Shaft Drilling Technology (ISDT) annual technical meeting*, Las Vegas, Nevada, April 18-21.

Rönnkvist, E., Friant, J.E., Ozdemir, L., 1994, "Development of a Mechanical Alcove Excavator for the Yucca Mountain Exploratory Study Facility", *Proc. International High Level Radioactive Waste Management Conference (HLRWM)*, Las Vegas, Nevada, May 22-26.

A New Concept for Selective Mechanical Mining of Hard Rock

Brian Asbury, Jamal Rostami, and Levent Ozdemir
Earth Mechanics Institute, Mining Engineering Department, Colorado School of Mines

MINI-CUTTER TECHNOLOGY - THE ANSWER TO A TRULY MOBILE EXCAVATOR

James E. Friant
Excavation Engineering Associates, Inc., Seattle

Levent Ozdemir and Erika Rönnkvist
Earth Mechanics Institute, Colorado School of Mines, Colorado

BACKGROUND

The single disc cutter was the key innovation influencing the successful development of the modern Tunnel Boring Machine (TBM). Early on, the cutter action was not well understood, but in 1956 the astounding tunnel advance record of 105 feet in one 24 hour period on a Toronto sewer job demonstrated the potential for the tunnel boring industry. That project set the stage for the next nearly 40 years of evolutionary development of both cutter and boring machine.

Development got off to a slow start. For the next 20 years, TBM manufacturers installed cutters in such a way that they cut concentric grooves about 3 inches apart. It was noted, however, that the harder a cutter was pushed, the further it sunk into the rock, and the faster the TBM went. The capacity of the disc cutters went from a humble 20,000 lbs for a 12 inch diameter cutter to 40,000 lbs for the new 15.5 inch cutter introduced in 1974 during the early phases of the Washington D. C. Metro Project, and on to today's 75,000 capacity 18 to 20 inch cutters. It wasn't until the mid to late 1970's that a research program at the Colorado School of Mines, was successful in developing a formulae which would describe the relationship between force on a cutter and its penetration (performance).

The recognized variables at the time included compressive and shear strength of the rock, diameter of the cutter, angle of the then triangular ring cross section, and the effect of spacing (distance between cuts). The original formulae developed and evolved along with the science, and naturally, it was computerized.

In the mid 80's, a rare opportunity for research in the field occurred as the Air Force missile program developed a deep base defense system. Millions of dollars in funding became available to study not only how to make a TBM go fast, but also to study how to make it go through fractured rock and rubble, and to give it the ability to turn from horizontal to vertical. These efforts contributed to the upgrading of the performance estimating program into a quite accurate science. Today, the most accurate of predictive programs take into account many more variables:

The Rock
Compressive strength
Tensile strength
Fracture spacing
Porosity
Grain size (and geometry in sandstone)
Hard mineral content

The Cutter
Cutter diameter
Blade width
Thrust capacity

The Machine
Thrust available
Torque available
Rpm

The Environment
Water inflow
Curves and slope
Rock support requirements
Human factors

Proceedings of North American Tunneling '94 Conference and Exhibition (NAT '94).
Denver, Colorado, June 6-9, 1994

TBMs became bigger, more powerful and more versatile machines using 17, 18.25, 19 and 20 inch cutters, routinely running at loads above 65,000 lbs of thrust each. Thus, the TBM designs evolved which had the size and structure to utilize the over 400 lb. disc cutter and its large saddle mount. All well for the big equipment, but for small bore sizes, technology nearly stood still. For a cutterhead less than 6 or 7 ft diameter, it became physically impossible to install a large high capacity cutter of the current design.

SMALL BORE TOOLS

The principal tools for smaller cutterheads are multi-row carbide insert cutters, or button row cutters, cone shaped cutters, strawberry cutters, and even some with random spaced buttons. Many of the applications for small cutterheads, or bits as they are called in some industries, derive their power and thrust through a drill string. Torque and power are more limited therefore, than on the huge direct drive TBMs. When faced with limited torque and thrust, the cutters will obviously indent the rock less and spacing must be reduced to assure that chips will form. Some cutter types have reduced spacing to the extreme, where they virtually pound the rock to dust.

As shown in Figure 1, a large penalty is paid for making small chips or powder. The curve shows the relationship between energy consumed by the machine and the average particle size generated. A ton of rock can be excavated with less energy if cuttings are brought out in large particles. In an instrumented test, an off-the-shelf 9 inch tri-cone bit required 80 hp-hr/ton in concrete and 120 hp-hr/ton in basalt. Compare this with 3 to 7 hp-hr/ton that disc cutters achieve on large diameter cutterheads. Yet the single rolling disc cutter has not found common application on small diameter excavating tools. There are perhaps two principal reasons for this:

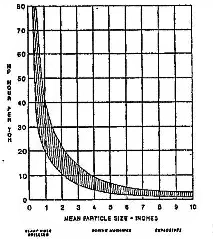

Figure 1. Excavation Energy Related to Particle Size

a) Those who have the technology of the disc cutter are primarily focused in the large bore industry. The importance of high thrust, maximum spacing (fewest cutters) and cutterhead balance is a closely held science. Large bore companies have not focused efforts on the small bore industry perhaps because they perceive greater profits in big bore jobs.

b) The smallest high production single discs are 15.5 and 14 inches diameter, while the smallest special order discs are 12 inches. Even the 12 inch cutters, with their husky saddle mounts occupy too much cutterhead "real estate" to use effectively on small diameter cutterheads. And, it is commonly believed by traditional manufacturers and users of single disc cutters that a cutter of significantly smaller diameter cannot be made robust enough to survive the high forces imposed by excavating hard rock.

THE 5.0 INCH MINI-DISC DEVELOPMENT

The incentive for designing a small disc started by playing iterative games with the predictive computer program. This exercise quickly showed that the two most effective ways of improving performance, among the "man-made" variablesdiscussed earlier, were cutter diameter and blade width.

Then there was the energy curve. TBM's were excavating a ton of rock for 3-7 hp-hr, while raise drills with multi-row, close spaced cutters were 20-30 hp-hr/ton. And as mentioned earlier, tri-cone arrangements and strawberry cutters were as high as 80-120 hp-hr/ton. There appeared to be much room for improvement.

LINEAR CUTTING MACHINE TESTS

Excavation Engineering Associates, Inc. (EEA) decided to take on the small disc challenge. Prototype cutters were designed and built in both a tungsten carbide version (left unit on Figure 2) and hardened all steel model (right unit on Figure 2). They are shown mounted on a heavy test pedestal. The first tests were run on the Linear Cutting Machine (LCM) at the Colorado School of Mines (CSM), Earth Mechanics Institute Laboratory (EMI) to determine the performance potential. This machine controls spacing and depth of cut, while recording thrust, drag and side loads on the cutter. A very hard 43,000 psi (297 MPa) rock was chosen to shake out any weaknesses as quickly as possible. Figure 3 shows this test series underway.

Figure 2. 5 Inch Mini-Disc, Pedestal Mounted

Results were beyond expectation. Figure 4 shows the most significant summary plot, the thrust vs. penetration curve. At 2.0 inch spacing, a penetration of .125 inch was achieved with only 11,700 lbs of thrust. To put this achievement into perspective, a standard 17 inch TBM cutter requires over 60,000 lbs to achieve this penetration in the same rock.

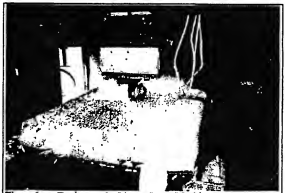

Figure 3. Testing on the Linear Cutter Machine

Also, the specific energy was measured and at 2.0 inch spacing was only 6.9 to 8.5 hp-hr/ton. This is far superior to the best multi-row or button type cutters ever tested.

FULL SCALE TESTS

Figure 5 shows an array of cutters which illustrates a desired profile for an 18 inch boring head with a basic cutter spacing of 1.9 inches. In this case, the cutters are all pedestal mounted. This configuration is satisfactory for competent ground, but when operating in soils with boulders or in highly fractured rock, cutters and pedestal mounts may be subject to damage.

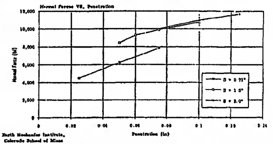

Figure 4. 5 Inch Mini-Disc Cutter Performance in 43,000 psi Rock

Since the Mini-disc is a cantilever design, the shaft can be built as an integral part of the cutterhead. A well is burned out in the forward plate of the cutterhead and the cutter shaft is welded into the cutterhead structure. In this way, the cutter is both recessed and protected. Rocks or boulders can not wedge between the cutters and damage the mounts. Figure 6 shows a typical inset cutterhead, in this example, 32 inches in diameter. In addition to the structural advantages, this style of mount allows changing of cutters from either side of the cutterhead.

The 32 inch cutterhead design employs both a cutting plan and a muck (cuttings) removal plan. Removing the muck from the face is equally as important as cutting the rock. The thrust on a rolling cutter increases when the cutter is forced to operate through previous cuttings. There are several undesirable effects including:

a) Cuttings are reground wasting energy.

b) An overturning moment is imposed on the cutterhead support system or bearing.

c) The cutterhead may have a tendency to self-steer.

Figure 5. Cutter Profile for 18 Inch Cutterhead

The cutterhead shown in Figure 6 pulls the muck off the face as it is cut. Muck does not fall by gravity to the invert of the tunnel where it must either be picked up again or must work its way rearward by the pressure of built up muck. In EEA's cutterhead design, muck is pulled immediately inside of the hollow head where it can be removed by auger, vacuum, gravity, air lift, or slurry depending upon the type of boring unit being used. As a box hole drill or raise drill head, a similar concept is envisioned except that the cutterhead would have a stinger built into the center of the cutterhead. The instant pickup feature ducts the cuttings immediately away from the cutters and prevents packing.

Figure 6. 32 Inch Mini-Disc Cutterhead

The cutterhead was also tested at EMI Laboratory. Again results were more favorable than expected. Figure 7 shows the performance results in 25,000 psi rock on the 25 rpm test, 33 ft/hr penetration rate was obtained with 82 hp! The thrust vs. penetration curve is the most favorable ever recorded by CSM. A small increase in thrust resulted in large increases in performance.

Specific energy was also exceptionally low at 5-8 hp-hr/ton similar to TBMs. Again the lowest specific energy ever recorded by CSM for cutterheads or drill bits of this size.

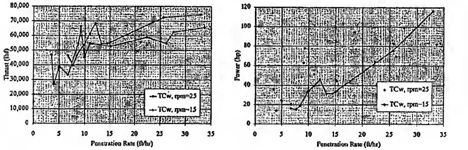

Figure 7. Performance of the 32 Inch Mini-Disc Cutterhead in 23,000 psi Rock

Figure 8 shows the cutterhead during test and Figure 9 shows the hole which was cut.

ADVANTAGES OVER CONVENTIONAL TOOLS

The tests described in this paper are only a few of an extensive test program. Both the carbide insert and the steel cutters have been extensively tested in various types of rocks with no failures. Only one cutter, a carbide insert type, was tested to destruction. It finally failed at 50,000 lbs thrust load. In actual practice, the penetration of the Mini-disc is so great that no more than an average of 15,000 lbs maximum should ever be required.

Figure 8. 32 Inch Cutterhead During Testing

Advantages over conventional tools for drilling, reaming and micro-tunneling are many, as follows:

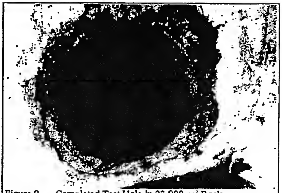

Figure 9. Completed Test Hole in 23,000 psi Rock

Flexible Spacing - In a multi-disc rolling cutter, spacing is fixed by design. If the three rows are, for example, positioned at 3 inches apart; the customer can have his choice of 3 inch spacing, or 1.5 inch spacing. With the single disc, if rock conditions call for 1.65 or 3.3 inch spacing, the cutters can be thus positioned for optimum performance. Cutter mounts take up so little space, very close spacing are possible.

True Rolling - Multi-row cutters skid. Typically, the better quality multi-row cutters are tapered or conical in shape to minimize skidding. However, a cone can only be true rolling at a single radius. One company makes a whole series of cone angles to achieve as close as possible to true rolling throughout the cutterhead. However, the user's inventory must cover all cone angles.

Some manufacturers compromise having only one cone plus a "strawberry" cutter in the center. Others use a cone, a strawberry and a gage cutter. All cone shaped cutters skid, some worse than others depending upon how far off the ideal radius they are positioned. Even when true positioned, one disc may hit an imperfection in the rock and dominate the rolling velocity of the other two.

A small single disc cutter is always true rolling. Cutters are interchangeable from center to gage.

Higher Performance - If 6,000 lbs of force is placed on a three row cutter, each row or disc receives 2,000 lbs with which to indent the rock. With a single disc cutter, if thrust is 6,000 lbs, the disc receives 6,000 lbs to indent the rock. Performance, being about proportional to force per disc, is much greater with a single disc. The same size rig will drill larger holes with lower torque, power consumption and thrust.

Single Tracking - When multi-row cutters are used, they overlap. This is particularly true when smaller spacing are used. This results in more than one disc running in a single track or

concentric kerf. Thus, while a single track disc may be penetrating say .1 inch, an overlapped, double tracking disc may penetrate at .05 inch. Forces and wear are thus not evenly balanced. Also, under these conditions there are more discs being used than are essential. Single tracking is the most efficient and cost effective cutting method.

Longer Wear - Because of the reasons above, minimal skidding, high performance (penetration) and single tracking, the single, true rolling cutter excavates more rock before it wears out. The Mini-disc carbide uses a complete ring, not buttons that turn or fall out. More carbide is used less discarded.

Ground Condition Tolerant - The same disc can be used in the hardest rock, in boulders and cobbles, in soft rock, coal, fire clay, and in free standing soil; all conditions but hydraulic soils. It is as close to the universal tool as science knows. A multi-row disc or button cutter tends to gum up in sticky ground. This will result in the cutter skidding and wearing a flat on one side. This will happen occasionally with a single disc too, but far less frequently. The tip of a disc cutter is sharp, like the prow of a ship and tends to push the dirt to the side. The multi-row cutter tends to pack the muck into the "valleys" between the discs and will gum up much quicker. Sometimes this packing causes a severe reduction of progress, sometimes skidding.

Low Cost Replacement - The strawberry cutter, commonly used in the center of a cutterhead must be burned off and a new assembly rewelded in place. Other multi-disc cutters which are saddle mounted are generally discarded whole. Some makes allow bearings or shaft parts to be reused. However rebuilding requires a shop with special tools. With the new Mini-disc, the cutter ring assembly is removed, discarded and replaced in the field with ordinary hand tools. One replacement cutter fits any position on the head. Figure 10 shows the assembly. Only five parts including a wear ring are involved.

Lower Initial Cost - The best news to a contractor is lower initial cost, as well as lower operating cost. All the advantages above, and yet a cutterhead with Mini-discs is less expensive than a cutterhead dressed with conventional cutters. If tungsten carbide inserts are required, the difference in cost is even more striking.

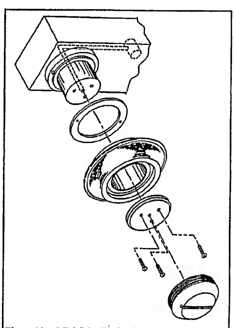

Figure 10. Mini-Disc Design Features

APPLICATION OF MINI-DISC CUTTER FOR MOBILE HARD ROCK EXCAVATOR

The mini-disc is highly suitable for application on mobile hard rock excavators. For the Exploratory Study Facility (ESF) at Yucca Mountain, Nevada, two feasibility and performance evaluation studies have been performed for mini-disc applications. From the main TBM tunnel alcoves will be excavated for scientific studies. The excavator for these alcoves must be compact and mobile with minimum disturbance to the activities in the main tunnel. For excavation of main test level openings at ESF, the potential application of mini-disc cutter roadheaders was examined. The main rock formation at ESF is welded tuff in which a large series of laboratory cutting tests have been performed with mini-discs. A standard roadheader with picks would not be able to cut this rock economically because of excessive bit wear, therefore a design and evaluation of a heavy-duty roadheader with mini-discs has been performed. Both of these feasibility studies gave very promising results, as discussed below.

MECHANICAL ALCOVE EXCAVATOR

It would be desirable to excavate the alcoves at ESF mechanically since blasting would not only damage the rock but would also require the dismounting of utilities and interfere with any activity further down the tunnel. Due to the special requirements, the excavator was designed to cut straight out from the main tunnel within a 12 ft by 12 ft transportation envelope. The power requirements on the alcove excavator has been kept to around 100 hp to minimize the size of the machine.

After several different cutting concepts had been studied for the excavation of the alcoves, a 6 ft drum appeared most promising. A concept drawing of the drum concept Mechanical Alcove Excavator is shown in figure 11. The performance and requirements of the excavator were investigated by developing a computer program based on data from prior mini-cutter tests. The drum plunges into the face a depth of 2.0 ft (0.61 m), it then slews across the top, moves downward, and slews across the bottom, covering the entire 11.5 by 21.3 ft (3.5 by 6.5 m) face. Upon completion of this action, an estimated 92 minutes, the plunge and slew procedure is repeated a second time. The machine is then "re-gripped". This is done using a hole drilled in the floor and set with hydraulic packers, rather than using bulky hydraulic grippers. After advancing the sliding platform 4.0 ft (1.2 m), two plunges can again be made. Total time for a complete cycle is estimated at 189 minutes (1.27 ft/hr, 0.39 m/hr).

Other interesting features of the machine include:

a) A hollow drum cutterhead which both cuts the rock and picks up the cuttings, transferring them by a short screw conveyor onto a 12 in. (0.30 m) transverse conveyor belt.

b) A 120 hp (90 kW) A.C. electric drive composed of two 60 hp (45 kW) motors.

c) Slewing by means of a 1.375 in. (35 mm) diameter cable powered by two winches.

d) A pantex lifting arrangement which maintains the axis of the cutterhead parallel to the axis of the tunnel.

e) A gripping technique consisting of a drill and two packer units.

f) Fluid spill mitigation incorporated in the design; electric drive, dry cutters, low oil volume, short hoses, catch trays, etc.

g) The roof, floor and ribs of the tunnel are smooth. Because of the slewing and pantex beam lifting device, no scallops are cut into the tunnel ribs (unlike a swinging action). Also the face is vertical, the most favored configuration for broken or highly fractured rock.

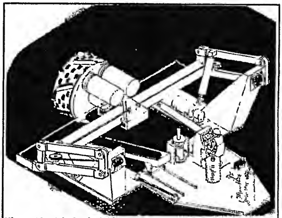

Figure 11. Mechanical Alcove Excavator

The configuration and performance of the Alcove Excavator make it suitable for excavating other side drifts and tunnels as may be required for the Exploratory Study Facility at Yucca Mountain. In the main test area a large number of tunnels will be excavated. By installing more power on this machine the test areas can be excavated quickly and a high production rate can be achieved. More power can be installed on the machine due to the fact that there will not be the same limitation on the size of the machine structure. One of the potential repository layouts suggests alcoves for storage of high-level radioactive waste and this excavator would be suitable for that purpose.

ROADHEADER APPLICATION

An extensive study was performed to investigate the technical and economic feasibility of using mini-disc cutters on heavy-duty roadheaders to excavate hard rock. A computer program was developed to evaluate various head shapes and cutter layouts using actual cutting data generated from laboratory testing of the mini-disc cutter. The results of the study have shown that heavy-duty roadheaders equipped with mini-discs can effectively attack and excavate hard-rock formations such as welded tuff in an economical manner. Laboratory tests will soon be performed with a roadheader cutting drum fitted with mini-discs. Following this will be a suite of field tests using a heavy-duty roadheader with mini-disc cutters. All studies and testing performed to date show great promise for this technology.

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DEVELOPMENT OF A MECHANICAL ALCOVE EXCAVATOR FOR THE YUCCA MOUNTAIN EXPLORATORY STUDY FACILITY

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ABSTRACT

A 25 ft (7.6 m) diameter tunnel, bored nearly 26,000 ft (8 km) long, is planned as the initial opening into a rather thick strata of welded tuff rock, known as Topopah Springs (TSw2). The near term purpose of the tunnel is to examine the geology to determine if the selected formation is suitable to be used as a nuclear waste repository. In addition to the tunnel, some 30 to 40 alcoves are envisioned along the tunnel which will serve as rooms in and from which the various scientists can conduct their analytical experiments. In addition, a series of rooms and hallways are planned in an area set aside as "the main test facility".

The overall site is known as The Exploratory Studies Facilities (ESF).

The entire construction is governed by a series of ESF DRs; a set of rules, regulations and limitations which are direct descendants of the Congressional Empowering Act. One of these, ESF DR 3.2.2.4 states, " *Ground should be excavated by mechanical means. When mechanical means are not feasible, controlled drilling and blasting methods shall be used*". Other sub tier orders limit blast damage to 300 mm outside the true line of the excavation. Based on results of controlled blasting experiments in other areas where the welded tuff formation was accessible, containing blast damage to within 300 mm of the excavation line appears unlikely.

The mission of this study program was to determine if a mechanical means of constructing the alcoves, rooms and hallways was feasible. Of particular interest were the alcoves which exit directly off of the main tunnel because:

a. Drill and blast work in these intersections would interrupt any work further down the tunnel including the Tunnel Boring Machine (TBM).

b. Structurally, blast damage at an underground intersection is the most deleterious.

c. Although a Determination of Importance Evaluation (DIE) has not yet been completed, the water injected, plus fumes injected plus fracture damage due to drill and blast operations may be found to radio nuclide movement.

The work for this study included determining a somewhat standard size for the initial alcove, determining whether existing equipment and/or technology was available, and determining if such equipment could be transported and launched from the main tunnel with minimum to no interruption to the main TBM operation.

The study determined that no off the shelf equipment was both capable of effectively cutting welded tuff, and sufficiently mobile to meet the minimum interruption requirements. The study did determine that suitable technology was available, and that a special purpose machine was feasible.

This paper describes the trade off studies conducted on various excavation methods, the system selected for conceptual design and the potential performance of a mobile alcove excavator.

1. INTRODUCTION

The main 5 mile (8 km) long tunnel planned for the ESF at the proposed nuclear waste repository at Yucca Mountain in Nevada, USA, will be the first opportunity to closely inspect the geology of the proposed repository horizon. In addition to the vast amount of in-situ

information to be gained from this tunnel, a number of alcoves are planned to permit more detailed scientific studies. It would be desirable to excavate these openings mechanically since blasting would not only damage the rock but would also require the dismounting of utilities and interfere with any activity further down the tunnel. This paper presents and discusses the feasibility study and performance evaluation of the Alcove Excavator.

II. BACKGROUND

At the time that this study was funded, April 1993, the then current 50% review drawings included alcoves at some 38 locations varying greatly in size and depth. The decision was made to focus on an 11.5 ft (3.5 m) high by 21.3 ft (6.5 m) wide by 40 ft (12.2 m) deep alcove. This provided for many of the requirements including being large enough to serve as a starter tunnel for the excavation of larger openings utilizing the biggest, most powerful, roadheader type machines on the market.

The requirements of the Mechanical Alcove Excavator included the following:

a. Small overall size to permit transport within the 12 by 12 ft (3.6 by 3.6 m) tunnel cross section dedicated to the transport vehicles.

b. Highly efficient cutting of the rock so that power and thrust requirements are kept to a minimum.

c. Minimum interference with tunnel utility lines.

d. Minimize time required to clear the tunnel sufficiently to facilitate single lane traffic.

e. Utilize proven technologies.

f. Incorporate the same fluid mitigation restraints as the Tunnel Boring Machine to be used for boring the main tunnel.

The overall objective of the project was to determine if a machine meeting all these objectives was feasible.

III. APPROACH

The basic excavation technology used in this study was based on data accumulated from commercial tests at the CSM Laboratory while testing a small disc cutter, 5 in. (127 mm) in diameter (Figure 1). This mini-disc was tested extensively at EMI both individually, in a linear cutting machine (LCM), and in a full scale 32 in. (0.8 m) cutterhead. These tests utilized Topopah Spring welded tuff unit #2 and Tiva Canyon rock samples. The attractiveness of this cutter was its exceptional penetration at low thrusts compared to other disc cutters being marketed. For example, the mini-disc achieved at 11,000 lbs. (49 kN) of thrust the same penetration as a conventional 17 in. (432 mm) cutter at over 40,000 lbs. (178 kN) of thrust. It is key to mobile excavator design that a suitable penetration be achieved with low power and thrust hence allowing the machine structure to be held to a minimum.

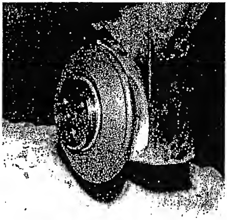

Figure 1. Mini-disc cutter

A computation based on the mini-cutter test data indicated that a sufficient excavation rate could be achieved while limiting the power to about 120 hp (90 kW), and thrust forces to about 100,000 lbs. (445 kN).

IV. METHODS OF CUTTING ROCK

Techniques of attacking the 11.5 by 21.3 ft (3.5 by 6.5 m) opening were studied from the standpoint of which cutting method utilized the cutters most effectively. Effective cutting of the rock is defined here as the proportion of the rock cut by disc cutters running repetitively in properly spaced parallel (or concentric) kerfs, as compared to the total volume of rock cut.

Four methods of cutting the alcoves were investigated:

a. Multiple plunging of a 4 ft (1.2 m) diameter drum cutter head.

b. A single 2 ft (0.6 m) plunge of the 4 ft (1.2 m) drum cutter head, followed by slewing the drum. Similar concept to Figure 2, the 6 ft (1.8 m) drum cutter head.

c. A single 2 ft (0.6 m) plunge of the 6 ft (1.8 m) drum cutter head, followed by slewing the drum (Figure 2).

d. A cutter wheel 6 ft (1.8 m) in diameter which plunges and slews over the face (Figure 3).

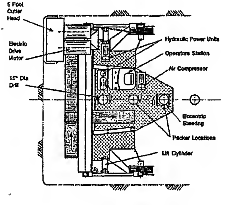

Figure 2. 6 ft (1.8 m) drum cutter head concept.

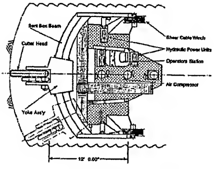

Figure 3. 6 ft (1.8 m) wheel cutterhead concept.

The percentage of rock cut efficiently by the different methods is shown in Table 1.

Concept	Type	Diameter	% cut efficiently
1	Plunging holes	4 ft (1.2 m) drum	53 %
2	Plunge and slew	4 ft (1.2 m) drum	58 %
3	Plunge and slew	6 ft (1.8 m) drum	60 %
4	Plunge and slew	6 ft (1.8 m) wheel	53 %

Table 1. Percent of rock cut in an effective manor.

The plunging head, Concept 1, was dropped at this point in the study and the latter three concepts were developed further. Two types of machine chassis were studied for each concept. One was based on a small chassied machine referred to as "partial cut machine". And the other on a full cut width machine, which could cut the entire face from one stance, referred to as a "full cut machine". The partial cut machines cut an alcove in several steps, six steps for the 4 ft (1.2 m) machine and four steps for the 6 ft (1.8 m) machine.

Performance, thrust variation and cutter head balance were investigated by creating a computer program based on the CSM data from prior mini-cutter tests. One important goal of the performance and balance program that was developed was to study the balancing of the cutter head during the slewing cutting action. In this cutting mode the cutters are moving in and out of the rock and during certain cutting actions have a constantly changing penetration depth. By simulating this with a computer program it was possible to design the cutter head to minimize the variation in resulting forces and therefore to create a stable cutting action which gives both a good performance and minimizes the structural requirements of the chassis.

At the same time the chassis layout of the units began. These took into consideration the restrictions imposed by the allocated transport space within the tunnel, an approximate cross section of 12 by 12 ft (3.6 by 3.6 m).

V. PREFERRED CONFIGURATION

As study commenced in the three areas of performance, thrust variation and physical layout, the 6 ft (1.8 m) drum plunge and slew cutterhead began to appear more and more promising.

The drum plunges into the face a depth of 2.0 ft (0.61 m), it then slews across the top, moves downward, and slews across the bottom, covering the entire 11.5 by 21.3 ft (3.5 by 6.5 m) face. Upon completion of this action,

an estimated 92 minutes, the plunge and slew procedure is repeated a second time. The machine is then "re-gripped". This is done using a hole drilled in the floor and set with hydraulic packers, rather than using bulky hydraulic grippers. After advancing the sliding platform 4.0 ft (1.2 m), two plunges can again be made. Total time for a complete cycle is estimated at 189 minutes (1.27 ft/hr, 0.39 m/hr).

Other interesting features of the machine include:

a. A hollow drum cutterhead which both cuts the rock and picks up the cuttings, transferring them by a short screw conveyor onto a 12 in. (0.30 m) transverse conveyor belt.

b. A 120 hp (90 kW) A.C. electric drive composed of two 60 hp (45 kW) motors.

c. Slewing by means of a 1.375 in. (35 mm) diameter cable powered by two winches.

d. A pantex lifting arrangement which maintains the axis of the cutterhead parallel to the axis of the tunnel.

e. A gripping technique consisting of a drill and two packer units.

f. Fluid spill mitigation incorporated in the design; electric drive, dry cutters, low oil volume, short hoses, catch trays, etc.

g. The roof, floor and ribs of the tunnel are smooth. Because of the slewing and pantex beam lifting device, no scallops are cut into the tunnel ribs (unlike a swinging action). Also the face is vertical, the most favored configuration for broken or highly fractured rock.

The performance model output indicates that the force and power requirements will be as in Table 2 below. A range is provided corresponding to the range of actual performance experienced in Welded Tuff during testing of the mini-disc.

Sumping mode	Calculated requirements	Balance during cutting
Sumping Thrust	112,900-131,900 lbs. 502-587 kN	Constant
Sumping Torque	26,300 - 28,400 ft-lbs 35.7 - 38.5 kNm	Constant
Sumping Power	70 - 80 hp 52.2 - 59.7 kW	

Slewing mode	Calculated requirements	Balance during cutting
Slewing Thrust	52,900 - 71,000 lbs 235 - 316 kN	± 3,200 lbs ± 14 kN
Slewing Torque	27,600 - 37,500 ft-lbs 37.4 - 50.8 kNm	± 1,450 ft-lbs ± 2.0 kNm
Slewing Power	80 - 110 hp 59.7 - 82.0 kW	

Table 2. Calculated thrust, torque and power requirements for the Alcove Excavator.

VI. GRIPPING MECHANISM

The light weight and small size of the alcove machine compared with Tunnel Boring Machines, roadheaders or the Robbins Mobile Miner dictates that the machine must in some way be fastened down. Grippers in the form of hydraulic shoes which brace against the tunnel walls are undesirable in the case of the full cut machine and impossible for the partial cut machine types. Shoe grippers are bulky, use large volumes of hydraulic fluid and in the case of a partial cut machine would have to reach unreasonably large distances to contact a wall.

Instead, drilling a hole in the tunnel floor and then inserting a packer into the hole was investigated. This technique would appear to be feasible and from an operational standpoint more acceptable. Packer components are standard parts.

VII. TRANSPORT VEHICLE

Figure 4 shows the Alcove Machine in its transport mode, and illustrates the fact that the machine fits within a few inches of the transport envelope. In the present configuration, the rear (sliding) platform is carried above the machine. Attachment of the sliding platform is the only mobilization assembly required.

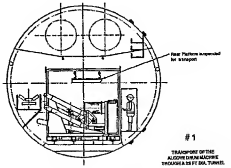

Figure 4. The Alcove Excavator in its Transport Mode

The complete transport train, consisting of two ramp-switch cars, the launch car and a support car is illustrated in Figure 5. The transport train rides on the outside rails of the dual track invert and is kept extremely low by using rollers on the rails. The platform contains a set of rails so that as soon as the Alcove Machine bores 6.0 ft (1.8 m) into the rock one way traffic through the tunnel is restored. The mobilization train functions as bridge and switches. This setup is shown in the plan view of the train, Figure 5.

To mobilize, the launch car is locked into the tunnel with jacks. The launch car also contains built-in "gripping" holes which provide the required stability for the initial cuts.

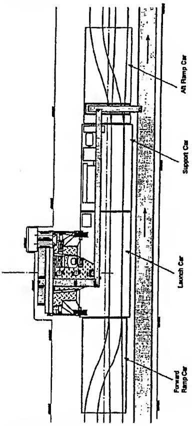

Figure 5. The Complete Transport Train

The support car contains a transformer, electrical controls, cable tray, drop box and a filter system. To control dust, a lower than ambient pressure is maintained in the cutterhead. Air is drawn through the muck pickup slots into the drop box and then through the filters. The same system is used to remove the cuttings generated by the drill which drills the holes in the tunnel floor for the packers.

CONCLUSIONS

The primary conclusion of this study is that a compact, relatively light weight, rail transportable alcove excavator machine is feasible.

A number of minor improvements to the design have been advanced since Figure 6 was conceptualized. However, the 6.0 ft (1.8 m) diameter drum machine design is still feasible. Establishment of a standard alcove size would allow a final decision on the optimal machine width.

The configuration and performance of the Alcove Excavator make it suitable for excavating other side drifts and tunnels as may be required for the Exploratory Study Facility at Yucca Mountain. In the main test area a large number of tunnels will be excavated. By installing more power on this machine the test areas can be excavated quickly and a high production rate can be achieved. More power can be installed on the machine due to the fact that there will not be the same limitation on the size of the machine structure. One of the potential repository layouts suggests alcoves for storage of high-level radioactive waste and this excavator would be suitable for that purpose.

The estimated performance output of the Alcove Excavator is presented in Table 3 below. The time requirements of maintenance, roof support, etc. were not taken into consideration in the estimated time requirements.

Performance	Results (US)	Results (SI)
Volumetric output	16.2 - 11.4 yd^3/hr	12.4 - 8.7 m^3/hr
Efficiency	2.9-5.7 hp-hr/ton	2.4-4.7 kW-hr/t
Advance rate	1.8 - 1.3 ft/hr	0.55 - 0.40 m/hr
Time to clear tracks (6 ft, 1.8 m)	3.3 - 4.7 hrs	3.3 - 4.7 hrs
Time to cut a 40 ft (12.2 m) deep alcove	22.2 - 31.1 hrs	22.2 - 31.1 hrs

Table 3. Estimated performance of the Alcove Excavator.

Condensed specifications for the machine are as follows (Table 4).

	US units	SI units
Alcove Face	11'6" high by 21'4" wide	3.50 m high by 6.50 m wide
Motors (2)	60 hp TEFC, NEMA 364T	44.7 kW TEFC, NEMA 364T
Slewing:		
force	75,000 lbs.	333.6 kN
rate	6.25 in/min @ 30 ton/hr	2.65×10^{-3} m/s @27.2 ton/hr
wire rope	1-3/8" 6x37	35 mm 6x37
Thrust		
force	132,000 lbs.	587.2 kN
cylinders (2)	8" dia @ 1,400 psig	203 mm dia @ 9.65 MPa
Cutter Head		
diameter	6'-0"	1.83 m
revolutions	14 rpm	14 rpm
No of cutters	35 ea. 5 in. diameter	35 ea. 127 mm diameter
gear reduction	11.7 : 1	11.7 : 1
guide rollers	VLRY 6-1/2	VLRY 6-1/2
Conveyors		
width	12"	304 mm
speed	200 ft/min	1.02 m/s
idlers	22°	22°
capacity	44 ton/hr	40 tonnes/hr
max. slope	15°	15°
Stroke	4'-0"	1.22 m
Overall Weight (estimated)	25 tons	22.7 tonnes

Table 4. Condensed specifications for the Alcove Excavator.

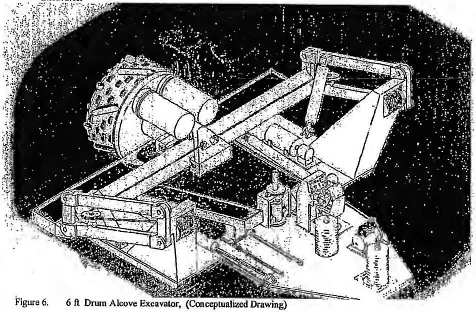

Figure 6. 6 ft Drum Alcove Excavator, (Conceptualized Drawing)

ACKNOWLEDGMENTS

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TESTING AND PERFORMANCE EVALUATION OF A 32 INCH CUTTERHEAD USING MINI DISC CUTTERS

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ABSTRACT

This paper presents the results of a laboratory test program to investigate the performance of a 32 inch diameter mini-disc cutterhead designed for hard-rock microtunneling applications. The cutterhead was fitted with twelve, 5-inch diameter mini-disc cutters. Laboratory testing and performance evaluation of the cutterhead was carried out at the rock boring laboratories of the Colorado School of Mines Earth Mechanics Institute (EMI). Tests were performed on samples of a limestone and a welded tuff formation. The mini-disc cutterhead was found to perform well beyond expectations, achieving very high rates of penetration in both rock types tested.

INTRODUCTION

Microtunneling is experiencing rapid growth worldwide. Because of its significant inherent advantages, microtunneling is becoming a more widely accepted technique in comparison to trenching techniques for the construction of utility, sewer and other types of tunnels, particularly in urban areas. Unlike surface trenching, microtunneling causes practically no surface disturbance, a very attractive feature for urban tunneling. It is estimated that the microtunneling market in the US is expanding at an annual rate of about 30 percent as the technology continues to improve and as potential buyers become aware of the significant advantages offered by microtunneling techniques.

Despite its tremendous market growth, microtunneling is still primarily restricted to application in soils and softer materials. The current technology of equipment in the field is not capable of effectively attacking hard rock. Furthermore, microtunneling machines usually encounter severe difficulties in mixed ground conditions where large hard boulders may be present. In such cases, the boulders have to be removed by sinking shafts or the tunnel alignment has to be altered, both options requiring additional time and cost. Hence, the microtunneling industry has been searching for a means of economically tunneling through hard ground or large rock boulders intermixed with soils.

In response to the needs of the microtunneling industry, EEA has designed and fabricated a prototype 32-inch diameter cutterhead fitted with the recently developed 5-inch diameter mini-disc cutters. Testing and performance evaluation of the mini-disc cutterhead was performed at EMI laboratories at the Colorado School of Mines. Testing was carried out in samples of two hard rock formations, the Indiana Limestone and the Tiva Canyon Springs Welded Tuff.

OBJECTIVES

The primary objective of the test program with the mini-disc cutterhead was fourfold:

1. To observe the physical operation of the cutterhead, cutters and muck collection buckets.

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2. To develop cutterhead performance data in terms of thrust, torque and power as a function of penetration rate.
3. To monitor and observe any wear to mini-disc cutters during the boring process.
4. To validate the computer models used in the design, performance evaluation and balancing of the mini-disc cutterhead.

In addition to these main objectives, the test program was also intended to produce cuttings for size analysis, as well as to check the operational stability of the cutterhead in terms of smoothness of operation.

LABORATORY TESTING

Test Equipment

Laboratory testing of the 32 inch mini-disc cutterhead was performed on the Drill Test Fixture (DTF). The DTF features a high-torque hydraulic drive system with variable speed capability up to 60 rpm. Cutterhead thrust is provided with a hydraulic actuator capable of generating up to 200,000 lb. of force. A swivel mounted on the backside of the drive system can be used for vacuum muck pickup or for routing cooling and dust suppression water to the cutterhead. The DTF has the thrust and power capacity to allow testing of cutterheads or drill bits up to 3 ft. in diameter.

Data Acquisition

The DTF is instrumented to measure thrust, torque, rotation rate and the rate of penetration during testing. Signals from various transducers are fed to a computer-based data acquisition and analysis system. This system is designed to provide real-time data display, as well as instantaneous output of data summaries upon completion of a test. With an added capability of allowing full analysis of test data in terms of interrelationships of various test parameters and the statistical evaluation of data acquired.

Rock Samples

Testing of the 32 inch mini-disc cutterhead was carried out in two rock types, Indiana Limestone (IL) and Tiva Canyon Welded Tuff (TCw). The uniaxial compressive strength of these rocks was 9,000 and 24,000 psi respectively. The TCw rock was used extensively in previous rock cutting research performed at EMI. Due to its "spongy" characteristic, (i.e. lack of the brittleness that is typical of hard rocks), TCw rock was found to respond to mechanical cutting as a rock type of a higher compressive strength. From the analysis of previously obtained cutting data it was found that the TCw formation behaves more like a rock having a compressive strength of around 30,000 psi.

The large samples of rock to be tested were cast in concrete with steel reinforcement to ensure proper support and confinement during testing. After curing, the cast samples were mounted on the DTF for the boring tests.

Mini-Disc Cutterhead

The cutterhead (Figure 1) is of the closed or shielded design, patterned after cutterheads designed for full-face tunneling in broken rock and mixed face conditions. The face shielding is intended to avoid the possibility of cutters being torn-off by broken rock and boulders. In operation, loose rock is held back and supported by the shield while the cutters break them into pieces small enough for passage through the muck buckets into the muck transport system. The cutterhead was fitted with radial muck pickup slots designed to capture a large portion of the muck

generated before it falls to the invert. This is intended to minimize muck regrinding and thereby reduce gage cutter wear and cutterhead friction.

Figure 1. Picture of the 32" diameter cutter head fitted with mini-disc cutters.

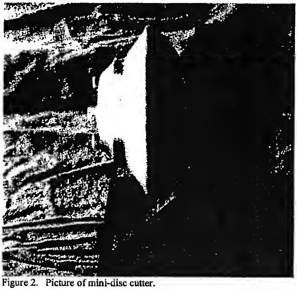

Figure 2. Picture of mini-disc cutter.

The mini-disc cutter was developed over a nearly two year period and was designed to provide a high performance and cost effective cutting tool (Figure 2). The primary challenge in this development was to find a bearing structure which would withstand the 30,000 lb. of load required to attack the hardest rock and to resist shock loading when a boulder is encountered. In addition, the cutter is designed for low cost and easy maintenance. When the ring wears out, it is simply removed and a new one mounted. This process automatically replaces the bearing and seal. All wear components are contained within the single cutter ring assembly.

Cutters were arranged in a double-spiral pattern with an average face spacing of about 2 inches. All cutters were fitted with the steel cutting rings, except for those at positions #3 and #12 which had carbide-insert rings. The purpose of using a mixture of steel and carbide-insert rings was to evaluate their relative wear performance during boring of the hard rock formations utilized in this test program.

After mounting the cutterhead on the DTF, the data acquisition and control system was checked for proper operation. Collaring of the sample was then commenced, it was continued until all of the cutters had established contact with the rock. Collaring was performed at a reduced machine thrust and rpm to ensure proper hole alignment and to avoid any cutter overloading which might result in premature damage.

Test Procedures

After collaring, testing of the mini-disc cutterhead was initiated (Figure 3). As stated previously, the primary objective of the test program was to develop sufficient data to evaluate the boring performance of the mini-disc cutterhead as well as to observe its operation with regards to cutterhead functioning, rock cutting and muck removal. These latter issues are as important to the success of the cutterhead in the field as is the performance data. Several aspects of the cutterhead design were considered critical to achieving its desired cutting efficiency.

Figure 3. The rock sample after several tests with mini-disc cutterhead.

1. Operational smoothness of the cutterhead by direct observation during testing.
2. Clearance between the face shield and the rock face.
3. Design of the cutterhead to keep the face clean during cutting.
4. Clearance between the face muck buckets and the rock face.
5. Proper cleaning of the face by the face muck buckets.
6. Proper cleaning of the invert by the side buckets.
7. Relationship between cutterhead rotational speed and efficiency of mucking.
8. The face tracking and cutterhead profile, as well as cut spacing and proper chipping between the adjacent cuts.

During and after testing the cutters were checked for any cutter wear or failure. Each test consisted of running the cutterhead at a preselected thrust and rotational speed. The test program included a total of 44 tests with 14 in the Indiana Limestone and 30 in the Tiva Canyon Welded Tuff.

TEST RESULTS AND DISCUSSION

The most interesting test results are presented in Figure 4 - 6. Figures 4 and 5 shows the tests results in Indiana Limestone and Figures 6 and 7 those in Tiva Canyon Welded Tuff. The graphs show the variation of penetration rate with thrust and power for two rotation rates in each rock type. Once a threshold thrust is exceeded a small increase in thrust will result in a substantial increase in the rate of penetration (Figures 4 and 6). That is, once chipping between adjacent cutting paths begins to occur and the rock cutting process enters its efficient operating regime a small thrust increase will result in a large increase in penetration rate. This is typical of rock excavation with disc cutters. For mini-disc cutters the threshold of efficient cutting force occurs at a significantly lower thrust value than for large disc cutters. In contrast, for a 17 inch cutter testing in welded tuff, efficient interaction between adjacent cutter paths was not seen to occur until a cutter load of approximately 20,000 lb. was reached.

Indiana Limestone

The mini-disc head was able to achieve very high rates of penetration with relatively low thrust requirements (Figure 4). For example, at 25 rpm, a penetration rate of 30 ft/hr was achieved at a cutterhead thrust of only 40,000 lb (Figure 4). Assuming even loading of cutters, this means the average cutter loading was 3,300 lb per cutter which is a fraction of what would be required with the standard size disc cutters. An important result is that similar to thrust, a cutterhead fitted with the mini-disc cutters would also need a very low torque compared to cutting with the standard, large size disc cutters presently employed on mechanical excavation equipment. Low torque means low power which accounts for nearly all the energy consumed in rock excavation. As shown in Figure 5, the mini-disc cutterhead was able to attain high boring rates with very low power requirements. Only 80 hp was required to maintain a penetration rate of 30 ft/hr in Indiana Limestone (Figure 5). Low thrust and power requirements as experienced with the test cutterhead have significant implications in the design of machinery utilizing this technology. Machine structure, size and weight requirements are dictated by the thrust, torque and resultant power requirements of the cutterhead. Thus significant cost benefits can be gained by the low torque and thrust needs of this cutterhead. Specific energy is the amount of energy required to excavate a unit volume of rock. In mechanical excavation systems, the specific energy is commonly used as an accurate indicator of the systems efficiency. Naturally, the lower the specific energy requirements, the more efficient the rock excavation system becomes. For the mini-disc head in Indiana Limestone, the average specific energy was 12 hp-hr/cyd of rock excavated. This low value further verifies the high cutting efficiency of the mini-disc cutters.

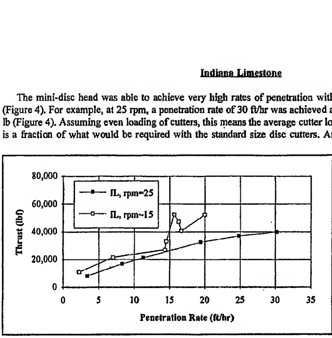

Figure 4. Plot of Thrust Vs. Penetration rate for Indiana Limestone

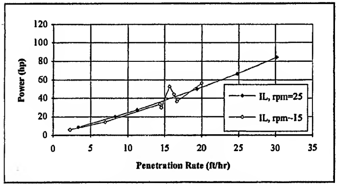

Figure 5. Plot of Power Vs. Penetration rate for Indiana Limestone.

Tiva Canyon Welded Tuff

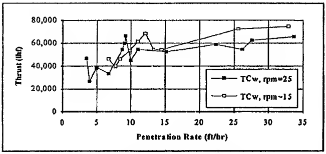

Figure 6. Plot of Thrust Vs. Penetration rate for Tiva Canyon Welded Tuff.

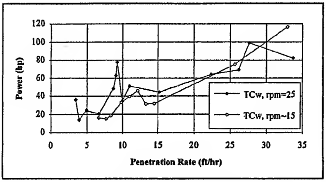

Figure 7. Plot of Power Vs. Penetration rate for Tiva Canyon Welded Tuff.

In the Tiva Canyon Welded Tuff sample the mini-disc cutterhead was able to achieve a penetration rate of approximately 33.5 ft/hr at a total cutterhead thrust of 65,000 lb at 25 rpm (Figure 6). This results in an average cutter loading of less than 5,500 lb per cutter. In contrast, when linear cutting tests were performed in this same rock with a 17 inch commercial size cutter the thrust to achieve the same depth of penetration was above 40,000 lb.

For the mini-disc cutterhead at 25 rpm, a 33.5 ft/hr rate of penetration only required a cutterhead torque of about 20,000 ft-lb., again confirming the very low torque requirements of the mini-disc cutters. Similarly, the cutterhead power requirements for the mini-disc head were found to be exceptionally low for excavation of welded tuff (Figure 7). At a cutterhead rotational speed of 25 rpm less than 90 hp was required to achieve a penetration rate of 33.5 ft/hr. The specific energy is again low, further confirming the very high cutting efficiency of mini-disc cutters as employed on the 32-inch cutterhead.

TEST OBSERVATIONS

As noted earlier in the test objectives and the procedures sections, in addition to acquiring performance data, a significant purpose of the test program was to observe the operation of the mini-disc cutterhead during testing. These observations were considered crucial to fully understanding and assessing the operational efficiency of the cutterhead. The most important observations made during testing included the following:

1. The cutterhead operation during the entire test program was extremely smooth, meaning it was well balanced and the cutter spacing and layout were properly selected. No unusual vibrations occurred during testing at different rotational speeds or cutterhead thrusts.
2. The clearance between the face plating and the rock surface was found to be adequate. No scouring was detected on the cutterhead plate. Very little paint was removed during the test series.
3. No packing of muck occurred on the cutterhead during boring.
4. The clearance between the face mounted muck buckets and the rock surface was correct as little wear was noticed on the bucket lips.
5. The position and size of the face muck buckets was correct. As was intended, the face mounted buckets were able to ingest a significant portion of the cuttings before they fell into the invert. This meant very little regrinding of muck in the invert and therefore, much lower torque consumption due to the reduced regrinding. It was estimated that only 20 percent of the muck fell to the invert.
6. The side buckets were also observed to operate satisfactorily, picking up any muck left in the invert by the face muck buckets. The invert received very little.
7. The preferred cutterhead speed of 25 rpm, as well as the optional cutterhead speed of 15 rpm, were found satisfactory for efficient mucking.
8. All cutters tracked properly and concentrically according to design profile (Figure 8).

No cutter failure or wear occurred during the entire test program. All cutters functioned properly. One cutter, No. 8, lost a hubcap during testing. Interestingly, the hubcap was picked up by a bucket immediately and was reinstalled. Its loss was not noted until after the test. The bearings and seals appeared to be unaffected by the test series. The carbide-insert cutters were in excellent condition. A small amount of scuffing was noted on cutters 1 through 6, but not on the carbide cutter installed in position 3.

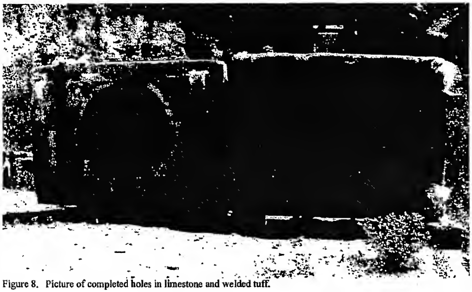

Figure 8. Picture of completed holes in limestone and welded tuff.

CONCLUSIONS

The mini-disc cutterhead performed well above expectations. The penetration rates attained in the two rock types tested were significantly higher than was estimated from computer models beforehand. The torque and power requirements to attain a given rate of penetration were also lower than expected. The high efficiency of mini-discs was further verified by the very low specific energy of excavation obtained from full-scale tests in the laboratory. In the 24,000 psi welded tuff, a penetration rate of 33 ft/hr. was achieved at 25 rpm with a total cutterhead thrust of only 65,000 lb. The power required to sustain this rate was less than 90 hp. As expected, the performance was even better in the 9,000 psi limestone where a penetration rate of 30 ft/hr was achieved at 25 rpm with a cutterhead thrust of around 40,000 lb. The cutterhead operation during the entire test program was extremely smooth due to proper balancing of the head and the correct selection of cutter spacing and layout. No unusual vibrations occurred during testing. The cutterhead face plate was free of scouring, indicating adequate clearance between the rock surface and the face plate. No packing of muck was found to occur on the cutterhead during testing. Test observations indicated that approximately 80 percent of the muck generated during boring was picked up by the face positioned muck buckets before falling to the invert. The side muck buckets were also found to operate satisfactorily, picking up any muck left in the invert by the face buckets.

All cutters tracked properly and concentrically according to design profile. No cutter failure or significant wear occurred during the entire test program. In particular, the two carbide-insert cutters mounted on the head were in excellent condition.

In summary, the test program was extremely successful in demonstrating the very high cutting efficiency of mini-disc cutters for microtunneling applications.

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Mini-Disc Equipped Roadheader Technology for Hard Rock Mining

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ABSTRACT

Results of an extensive study on the application of Mini-disc equipped heavy-duty roadheaders in hard rock mining is presented in this paper. The study included laboratory testing and computer modeling to assess the technical and economic feasibility of utilizing Mini-disc cutters on roadheader cutterheads. The results show that heavy duty roadheaders fitted with Mini-discs can excavate hard rock formations at acceptable production rates and cutter costs.

INTRODUCTION

Roadheaders have been considered for application in underground hard rock mining for a long time. This is due to their capability to excavate various shapes and sizes of openings. In addition, they have flexibility, mobility, ability to make sharp turns, and provide immediate access to the face. Altogether, they are ideal machines for development in underground hard rock mining.

To be useful to the hard rock operation, a roadheader would have to successfully attack highly abrasive and strong rock formations. These conditions are beyond the capability of even the largest, most powerful roadheaders available today and equipped with pick or point attack cutting tools. The tools wear out so rapidly that even if excavation is possible, it is uneconomical. These limitations of the roadheader are well known.

If disc cutters could be utilized on a roadheader, the application of this type excavator could be extended into harder rocks. While disc cutters have become the standard tool for hard rock excavation, commercially available discs are too large, occupy too much mounting space, and require thrust levels too high to be feasible on a roadheader. However, in 1992 a high thrust capacity, cantilevered, 125 mm (5 in.) diameter disc cutter was developed at the Earth Mechanics Institute (EMI) of the Colorado School of Mines (CSM). Since then it has been tested in various rocks including some hard abrasive rock samples (up to 275 MPa (40,000 lbs) in compressive strength) with excellent results. High penetrations were achieved with very low thrust levels. Further, when used with a pedestal mount, the cutter assembly takes up very little room on the cutterhead. More cutters can be installed to achieve a smoother operation and cutters can be closer spaced to achieve successful excavation of hard rock with limited force. Lower force and space requirements of the Mini-disc combines the advantages of drag type and roller type cutters. This allows utilization of disc cutter technology on roadheaders for hard rock applications.

BACKGROUND

Roadheaders have traditionally operated in sedimentary rocks with unconfined compressive strength less than 100 MPa (15,000 psi). Occasionally, harder rocks have been excavated where joints, bedding planes, fractures or other planes of weakness were present. As rock strength and in particular the silica content increase, the performance of roadheaders drops dramatically. The reasons for this have been discussed quite extensively in the literature (Neil & Ozdemir 1991).

Among the various solutions offered in the past few years, Mini-disc cutters on heavy-duty roadheaders seems to be promising. EMI performed a detailed study of the concept including an several full-scale linear cutting tests in selected hard rocks. The results were used to develop a computer model for evaluation of the technical feasibility and performance of a Mini-disc roadheader cutterhead. This was followed by the design and fabrication of a prototype cutterhead for a transverse type roadheader. The cutterhead was then used in full-scale laboratory cutting tests to simulate operating modes such as sumping and sheardown. The results of these tests discussed in this paper, proved the technical feasibility and the capability of Mini-disc fitted cutterhead in cutting hard rock.

CUTTERHEAD DESIGN FEATURES

The cutterhead of a 100 ton class Voest-Alpine (VA) AM-105 roadheader was the basis for the design of the prototype cutterhead for laboratory testing. A joint design effort was initiated with the VA technical staff.

Computer modeling indicated the performance of the Mini-disc cutterhead would be limited by the arcing force available on the machine. The maximum amount of side force that could be applied to the cutterhead was restricted by the machine weight and the friction between the crawlers and the floor. Even on a machine with 100 ton weight the side or arcing force capacity is around 15 tons. Beyond this limit, the machine will move sideways without being able to penetrate the rock. Since the typical normal force requirement of Mini-disc cutters for efficient penetration into hard rock is about 4-5 tons, the machine can only support 3 to 4 cutters in contact. Obviously this is not sufficient to provide efficient and productive cutting operation. Moreover, with so few cutters, the head vibrations would be excessive and could damage the cutters and the gearbox assembly. Tracking of the cutters, which is a crucial issue in disc cutting, is harder to maintain in arcing mode.

To eliminate these problems, the machine must operate differently it normally does. The solution to this problem is to operate the machine in sumping and sheardown modes to overcome the limits and problems of arcing. This means that the cutterhead must sump into the face of the tunnel at the top and move down towards the floor without any side movement. This sheardown action allows cutters to track while facilitating better use of the machine (and cutterhead) mass during the cutting operation. This decision consequently led to some changes in the original cutterhead design, as follows.

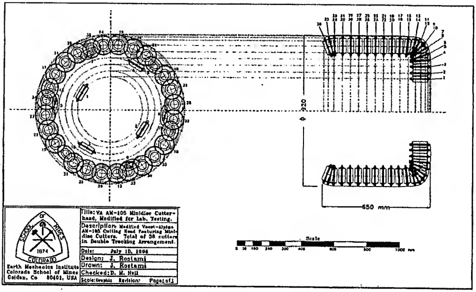

Figure 1. Design of the prototype Mini-disc cutterhead.

The cutterhead geometry was selected to be cylindrical to accommodate tracking of the cutters, as well as to reduce the number of cutters in contact with the rock. Diameter of the head was selected at 920 mm (36 in) and the length of the head at 785 mm (30 in). The diameter of the head does not effect the results of the modeling or testing due to the particular modes of cutting (sump/sheardown) designated for the machine operation.

The cutter spacing was set at 50 mm (2 in) in the face area. This spacing was selected to provide a good cutterhead balance while maintaining high cutting efficiency. Cutter positions on the profile and their respective tilt angles were selected to avoid excessive side forces on the cutters (Figure 1). Once these parameters were established, the general cutterhead profile was defined and the 3D cutter pattern was developed.

The computer program specifically developed for cutterhead design and simulation was then used to balance the head with an even distribution of cutters and loads. This program was also able to monitor force and torque variation on the head to minimize vibrations during cutting, which is an important issue for head stabilization. Balancing of the cutterhead was included in the design of the prototype head to improve cutting efficiency and to minimize cutter wear. The optimum angular spacing, the angle between adjacent sets of cutters, was determined and the angular position of each cutter was defined by the program.

Cutterhead force and torque requirements were then predicted for a given depth of sump and penetration per revolution. Performance and production capability of the machine in each mode

were estimated by determining the area of the cutting surface and the maximum achievable boom speed for a given depth of sumping.

CUTTERHEAD FABRICATION

After several design reviews, the final head design and cutter layout were developed and the head was fabricated at the Voest Alpine production facility in Zeltweg, Austria. The final cutterhead design was modified by the cutterhead manufacturer, from the original design of the Mini-disc cutterhead. The changes deemed necessary by the design engineers were to move the nose cutters to the gage area and to create a double tracking pattern. Another change was to arrange the cutters in a chevron pattern to start the cutting at the middle and move towards the gage area. Figure 2 shows a schematic 3D drawing of the final cutterhead design.

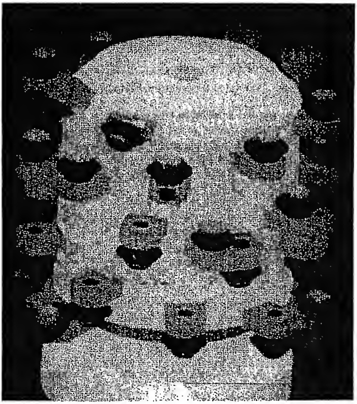

Figure 2. The schematic drawing of the prototype cutterhead with Mini-disc cutters.

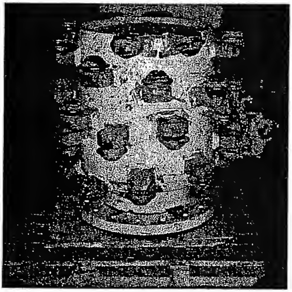

Figure 3. Picture of the prototype roadheader cutterhead.

Overall, the cutterhead geometry and cutter placement were made symmetric to achieve a more or less even cutter loading and to avoid side movement of the cutters for better tracking. There is a cutter in every 10° in the final design (Figure 3). The cutterhead was shipped to the EMI laboratory for full scale testing of the two cutting modes. The cutterhead was tested in samples of hard rock using the EMI Drilling Test Fixture (DTF) which allows testing of both sumping and shearing modes of cutting (Figure 4).

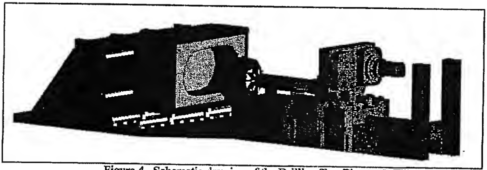

Figure 4. Schematic drawing of the Drilling Test Fixture (DTF).

TEST PROGRAM

The test program was designed to provide data on cutterhead performance in the two cutting modes designated for operation in the field. Testing was accomplished by casting a rock sample in the rock box with a void located to allow the cutterhead to simulate the desired mode of cutting. The sample used in this test had a UCS of about 83 MPa (12,000 psi) with tensile strength of 8 MPa (1,150 psi). The mechanism for sumping was to rotate the cutterhead in place and translate the rock sideways towards the head. This forced rock engagement along 50% of the cutterhead perimeter. Several tests were conducted at different levels of thrust while all operating parameters including rpm, torque, side thrust, and the advance rate were measured by the data acquisition system. The maximum thrust was limited by the capacity of the support bearings. Figure 5 shows the setup for the sumping tests.

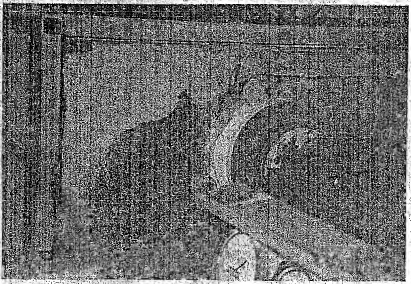

Figure 5. Setup for sumping tests.

Sheardown simulation tests were run in a similar manner but the cutterhead was engaged only along less than 25 % of its perimeter (Figure 6). The sample used in this test had a UCS of about 135 MPa (19,600 psi) with tensile strength of 12 MPa (1,720 psi). The tests were run at various thrust levels to monitor the penetration rate variation. The depth of shearing was approximately 400 mm (16 in) which was slightly above the depth of sump designated for sheardown operation in the field. In actual operation, multiple sumping will be necessary to bypass the clearance (sumping) limit between the cutter tips and the gearbox. This can be seen in Figure 6.

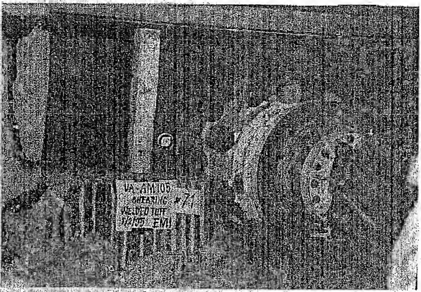

Figure 6. Set up for shear down tests.

TEST RESULTS

Tables 1 and 2 contain the results of testing with the Mini-disc cutterhead for sumping and shearing tests, respectively. The maximum penetration rate attained was 1.2 mm (0.01 and 0.048 in/rev) at a thrust level of about 123 kN (28,000 lbs). This is equivalent to a boom speed (sumping speed) of 3 m/hr (6.2 ft/hr) at 26 rpm. The power requirement was below 34 kW (45 hp) at this penetration rate. The specific energy, which was calculated from the power and the volume of rock produced, ranged from 34 to below 20 kW-hr/m^3 (hp-hr/yd^3).

The thrust force limitation of the DTF did not allow for higher cutter forces to achieve deeper penetrations into the rock surface. As a result, the cutting performance was not as efficient as could be obtained in the field. The penetration rates experienced were below the critical penetration. Penetrations above the critical depth directly translate to higher productivity with lower energy and more efficient cutting.

The maximum thrust used in the testing was about 60% of the available VA AM-105 sumping force of about 50 tons under dry floor conditions. Also, the maximum power consumption experienced during testing was about 25% of what is available on the AM-105, which is 300 kW (400 hp). Figures 7 and 8 show the results of sumping tests along with the best fit curves.

Table 1. Results of sumping tests.

VA Mini-disc Cutterhead in Welded Tuff TSw2 #120								Test Date:	17 - 22 Nov 94	
Test/ Measurements During The Sumping								Thrust/	Torque/	Specific
Test #	Sump	RPM	Torque	Thrust	IPR*		Power	Area	Area	Energy
	(in)	(rpm)	(ft-lbf)	(lbf)	(ft/hr)	(in/rev)	(hp)	(lbs/ft^2)		(hp-hr/cyd)
2	2	27.1	2,862	7,921	4.5	0.033	14.8	2,378	859	27.6
3	4	27.7	3,448	8,781	4.3	0.031	18.2	1,846	725	26.2
4	5	27.0	4,491	13,843	7.7	0.057	23.1	2,552	840	16.7
5	6.75	26.7	6,330	14,445	5.0	0.038	32.2	2,304	1,010	31.7
6	7.8	26.3	7,590	17,569	5.4	0.041	38.0	2,592	1,120	32.7
17	14.00	27.8	2,923	12,186	2.5	0.018	15.5	1,293	310	24.7
18	14.30	26.9	2,868	13,477	2.1	0.015	14.7	1,412	300	27.9
19	15.00	27.9	3,376	15,061	2.3	0.017	17.9	1,533	344	30.2
20	15.50	26.8	4,074	16,012	2.5	0.019	20.8	1,598	407	32.6
21	16.30	26.7	4,668	18,422	2.9	0.022	23.7	1,783	452	31.7
22	17.00	26.7	5,328	20,111	3.0	0.023	27.0	1,896	502	34.6
23	18.00	26.4	5,942	21,629	3.6	0.027	29.9	1,967	540	32.1
24	18.00	26.6	6,580	22,826	4.2	0.032	33.3	2,076	598	30.4
25	18.00	27.1	4,784	18,261	2.9	0.021	24.7	1,661	435	33.3
26	18.00	26.6	5,862	21,716	3.9	0.030	29.7	1,975	533	29.0
27	18.00	26.3	7,146	24,478	4.4	0.033	35.8	2,226	650	31.6
28	18.00	26.1	7,715	26,259	4.9	0.038	38.3	2,388	702	30.0
29	18.00	27.1	3,199	11,592	1.8	0.014	16.5	1,054	291	34.7
31	18.00	26.6	7,106	24,065	4.3	0.032	36.0	2,189	646	32.2
32	18.00	27.0	7,086	25,302	5.9	0.044	36.4	2,301	644	23.7
33	18.00	25.9	9,152	28,206	6.2	0.048	45.1	2,565	832	28.2

Table 2. Results of shear down tests.

VA Minidisc Cutterhead in TSw2 #104									Test Date:	Jan 3-4, 1995	
	Shear								Thrust/	Torque/	Specific
Test #	Distance	Sump	RPM	Torque	Thrust	IPR*		Power	Area	Area	Energy
	(in)	(in)	(rpm)	(ft-lbf)	(lbf)	(ft/hr)	(in/rev)	(hp)	(lbs/ft^2)	ft-lbs/ft^2	(hp-hr/cyd)
71	4	16	25.3	945	1,348	2.9	0.023	4.6	666	467	21.1
72	5	16	24.7	1,970	2,770	5.0	0.041	9.3	1,197	851	21.5
73	7	16	24.0	2,471	4,136	6.1	0.051	11.3	1,459	872	17.6
74	11	16	24.2	4,851	6,480	6.9	0.057	22.4	1,736	1,299	23.6
75	12	16	23.6	5,369	8,405	7.1	0.061	24.1	2,132	1,362	23.1
76	14	16	22.0	6,906	11,797	9.4	0.085	28.9	2,714	1,589	19.2
77	16	16	23.8	9,674	14,147	11.9	0.100	43.9	2,985	2,041	21.0
78	17	16	22.2	13,072	17,399	14.7	0.133	55.2	3,525	2,649	20.5
79	17.8	16	23.7	5,409	8,133	5.2	0.044	24.4	1,598	1,062	25.0
80	17.8	16	23.9	7,952	11,566	7.0	0.059	36.2	2,272	1,562	27.3
81	17.8	16	23.3	10,172	14,416	8.7	0.075	45.2	2,832	1,998	27.4
82	17.8	16	23.4	13,048	17,812	12.3	0.105	58.1	3,499	2,563	25.0
83	17.8	16	22.0	18,098	22,087	23.6	0.215	75.9	4,339	3,555	17.0

1 in. = 25.4 mm , 1 lb. = 0.453 kg = 0.0044 kN , 1 ft. = 0.305 m

* Instantaneous Penetration Rate

The results of sheardown testing are summarized in Table 2. The thrust levels used in the main test set were between 28 kN and 97 kN (6,500-22,000 lbs). Tests were run at 23 rpm and the maximum power requirement was below 57 kW (76 hp). The penetration rates reached over 5 mm/rev (0.21 in./rev) and the shearing speed was about 7.2 m/hr (23.6 ft/hr). The cutterhead production at this rate was close to 3.5 m^3/hr for one head (7 m^3/hr for the machine). The

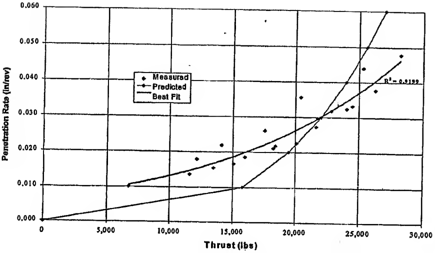

Figure 7. Penetration as a function of sumping force for sumping tests.

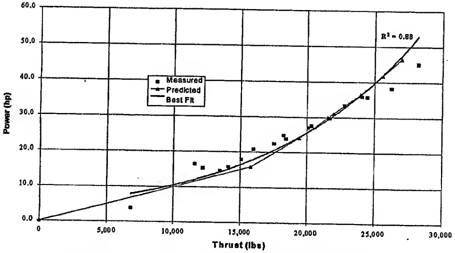

Figure 8. Power as a function of sumping force for sumping tests.

penetration depth achieved at this force level is over the threshold or critical penetration and consequently a significant drop in specific energy can be observed. The minimum specific energy value encountered in the shearing tests was 17 kW- hr/m^3 (hp-hr/yd^3),even though the rock sample tested was harder and stronger than used in the sumping test. This shows the effect of deep penetration on cutting efficiency. The shearing force used in this test is below the AM-105 roadheader lowering force capacity and the power requirement is 40% of the installed cutterhead power. Higher production rates and more efficient cutting can be attained with the actual machine in the field due to its ability to apply more force and power and thus achieve deeper penetrations. Figures 9 and 10 show the results of the shearing tests and their best fit curve.

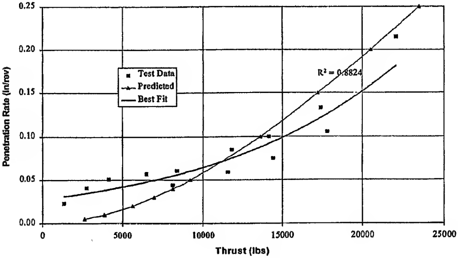

Figure 9. Penetration as a function of shearing force for sheardown tests.

Using the measured power consumption and production rate, the specific energy required by the cutting process was calculated to reach a minimum of 21 kW-hr/m^3 (hp-hr/yd^3) in sumping and 17 kW-hr/m^3 (hp-hr/yd^3) for shearing tests. Based on the specific energy values measured in laboratory testing, the field production rate of the AM-105 with Mini-discs in welded tuff is estimated at 12 to 15 m^3/hr. This rate reflects excavation of massive welded tuff with no major discontinuity or joints. Obviously, the presence of joints or other rock weaknesses would contribute to higher production rates.

COMPARISON BETWEEN MEASURED AND PREDICTED PERFORMANCE

One of the primary goals of the program was to validate the computer models used for the design and performance prediction of the Mini-disc cutting head. To accomplish this, the thrust

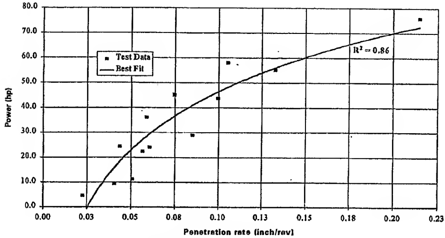

Figure 10. Power as a function of shearing force for shearing tests.

and power required to achieve a certain depth of penetration at a given depth of sump was predicted with the program and compared to what was actually measured in the tests. Figures 7 and 8 compare the measured and predicted parameters for the sumping tests. Figures 9 compare the measured and predicted parameters for the sheardown tests. As can be seen, there is a close agreement between the predicted and the measured performance.

The observed deviation between the predicted and the measured parameters in some cases is believed due to using data from linear cutting tests or other drilling tests with higher penetrations in the modeling. This means that the prediction was based on a more efficient cutting regime and would therefore overestimate the cutting capability of the cutterhead at low penetrations. The predicted and measured parameters seem to converge as higher penetration. In the sheardown tests, the prediction for torque and power was below what was measured in the test. This was caused by the accumulation of rock cuttings at the cutting face which resulted in a higher torque requirement. Obviously, such a degree of muck accumulation and regrinding does not occur in the field.

CONCLUSIONS

The laboratory full-scale testing of the Mini-disc equipped roadheader cutterhead was very successful, further demonstrating the great promise that this technology offers for efficient excavation of hard rock formations with heavy-duty roadheaders. In both the sumping and shearing tests, the Mini-disc were found to penetrate and chip efficiently with a total cutterhead thrust, torque, and power requirements well below what a heavy-duty roadheader is capable of generating. The cutterhead was observed to run very smoothly during both sumping and shearing tests, proving the well-balanced head design and cutter layout. Based on the evaluation of vibration data recorded during testing, no significant mode of vibrations which could cause

potentially harmful cutting boom resonance were observed. No type of cutter wear or structural failure was found to occur during the entire laboratory test program. These observations, combined with data from a recently completed microtunneling job and other ongoing test programs clearly confirm the durability and robustness of the Mini-disc, even in the excavation of very hard and abrasive rock formations.

One of the major goals of the test program, the validation of the computer models developed and used for head design and performance prediction, was also successfully achieved. A very close correlation was obtained between the measured and the predicted cutting performance. This means the developed computer models are capable of providing accurate and reliable estimates of attainable field performance while allowing for optimal and properly balanced head design and cutter layout. Field testing of a roadheader with a Mini-disc cutterhead will soon commence in a hard rock formation. These tests will include sumping and sheardown modes of cutting, allowing direct evaluations of productivity, cutter wear, and overall excavation costs.

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Electronic Patent Application Fee Transmittal

Application Number:	10688216
Filing Date:	15-Oct-2003
Title of Invention:	Automated excavation machine
First Named Inventor/Applicant Name:	Eric Jackson
Filer:	Douglas W. Swartz/Debra Kesner
Attorney Docket Number:	4770-37

Filed as Large Entity

Utility Filing Fees

Description	Fee Code	Quantity	Amount	Sub-Total in USD($)
Basic Filing:				
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Claims:				
Miscellaneous-Filing:				
Petition:				
Patent-Appeals-and-Interference:				
Post-Allowance-and-Post-Issuance:				
Extension-of-Time:				

Description	Fee Code	Quantity	Amount	Sub-Total in USD($)
Miscellaneous:				
Submission- Information Disclosure Stmt	1806	1	180	180
	Total in USD ($)			**180**

Electronic Acknowledgement Receipt

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International Application Number:	
Confirmation Number:	7252
Title of Invention:	Automated excavation machine
First Named Inventor/Applicant Name:	Eric Jackson
Customer Number:	22442
Filer:	Douglas W. Swartz/Debra Kesner
Filer Authorized By:	Douglas W. Swartz
Attorney Docket Number:	4770-37
Receipt Date:	18-DEC-2006
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Time Stamp:	15:43:12
Application Type:	Utility

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RAM confirmation Number	246
Deposit Account	191970
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2	NPL Documents	ANewConceptForSlectiveMechanicalMiningOfHardRock.pdf	1641047	no	8
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